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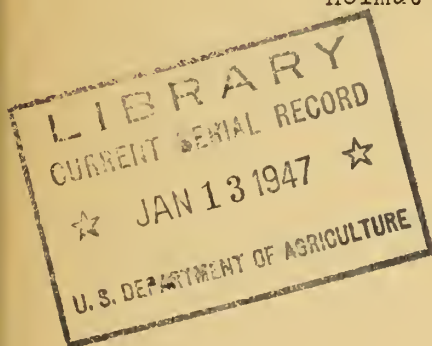
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MOISTURE RELATIONS OF TIRE CORDS IN TIRES

By

Helmut Wakeham, Edith Honold, and H. J. Portas



Southern Regional Research Laboratory
New Orleans, Louisiana
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 Southern Regional Research Laboratory
 New Orleans, Louisiana

The moisture content of a textile fabric has considerable influence upon its physical properties and upon its chemical degradation at elevated temperatures. Cotton cords, for example, generally increase in breaking strength with an increase in moisture content; whereas rayon shows a decrease in strength with increase in moisture. Other properties, such as elongation and similar elastic behavior, are likewise affected. These facts indicate that a thorough knowledge of the moisture contents in tires is essential in setting up test procedures and in studying the performance of cords in tires.

Opinions concerning the moisture contents of cords in tires were found to be so divergent that an experimental study of this factor using actual tires seemed desirable. Previous investigations on the moisture relations of textiles and rubber and on the rates of moisture diffusion in rubber indicate that the moisture contents of cords in the tire will depend somewhat on external conditions as well as upon the conditions within the tire during service. These researches leave unanswered, however, questions concerning the moisture gained or lost by the cords during certain manufacturing operations, such as in the vulcanization of the tire, during storage, or during service. In the present work temperature, humidity, and time, the most important determinants of moisture in the tire, were investigated to gain some information concerning the effect of these parameters on the moisture contents in tires under various conditions.

Data available in the literature lead to the conclusion that moisture transpires through the outer layers of rubber on a tire with relative ease. Edwards and Pickering^{3/} reported that the relative permeability of rubber to water vapor is approximately 50 times that to hydrogen, that the permeability is proportional to the partial vapor pressure of the water, and that the amount of vapor passed varies inversely with the thickness of the rubber. These findings were extended by later investigators^{4/} who showed that the

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^{2/} Southern Regional Research Laboratory, New Orleans, La. One of the laboratories of the Bureau of Agricultural and Industrial Chemistry, Agricultural Research Administration, United States Department of Agriculture.

^{3/} Chem. Met. Eng., 23, 17 and 71 (1920).

^{4/} E. E. Schumacher and L. Ferguson, Ind. Eng. Chem., 21, 158 (1929).

R. L. Taylor, D. B. Herrmann, and A. R. Kemp, Ibid., 28, 1255 (1936).

H. A. Daynes, India Rubber World, 97, 2, 49 (1937); "Proceedings of the Rubber Technology Conference, 1938," p. 886. W. Heffer & Sons, Ltd., Cambridge, 1938.

R. L. Taylor and A. R. Kemp, Ind. Eng. Chem., 30, 409 (1938).

passage of moisture through rubber is greater than that predicted by the simple diffusion laws because of the concomitant sorption process which takes place. The rate of passage or approach to equilibrium increases with temperature so that at high temperatures the cord in a tire would be expected to come to moisture equilibrium in less time than at some lower temperature. Doty, Aiken, and Mark^{5/} found that for substances, such as rubber, which contain hydrophilic material the permeability to water vapor is dependent upon the thickness of the layer. This factor would be of some importance in considering the moisture transmission in the heavier truck and bus tires.

Lyons and coworkers^{6/} carried out experiments on the moisture sorption at room temperatures of tire cords vulcanized in thin slabs of GR-S. These slabs were put through a cycle of exposure to humid and arid atmospheres while the weights of the slabs and the regains of the cords were followed. The rayon and cotton cords both increased in moisture content at a rapid though decreasing rate for the first 20 to 50 days during the humid portion of the cycle. After about 70 days the rate of moisture increase was approximately constant up to about 200 days. The results indicated that although rayon fabric in rubber picks up a larger amount of moisture than cotton cords (15% as compared to 5% for cotton), under dry conditions it loses this moisture more rapidly than cotton. Both types of cord exhibited some inertia with respect to moisture sorption or desorption. When a slab containing cotton cords was cut so that the cord ends were exposed directly to moisture vapor, the rate of moisture exchange increased markedly.

The foregoing information predicts in a general way the trends of moisture exchange between the cord in the tire and the outer atmosphere, but does not permit accurate evaluation of tire cord moisture contents because of the complexity of tire construction and indeterminate factors connected with tire manufacturing procedure. Actual moisture contents of cords in tires must be measured if information of this type is desired.

PROCEDURE AND CALCULATIONS

The problem of determining moisture contents of cords in tires was, in brief, one of removing the cord from its rubber sheath in the tire and placing it into a weighing bottle without permitting appreciable moisture exchange with the surrounding atmosphere. The conditions of transfer were found as follows. A rough estimate of the moisture content of the cord was made from known conditions of tire manufacture and from the recent history of the tire. Atmospheric conditions which would minimize moisture exchange were then chosen, using as a guide the data of Wiegerink^{7/} on moisture relations of textile fabrics, along with exploratory determinations of the weight changes observed with the exposure of freshly stripped cords from the tire. These conditions were then approached as nearly as practicable in a special temperature- and humidity-controlled room in which the cords were pulled from the tire.

^{5/} Ind. Eng. Chem. (Anal. Ed.), 16, 686 (1944).

^{6/} Southern Regional Research Laboratory, private communication.

^{7/} J. Research Natl. Bur. Standards, 24, 645 (1940).

The cords actually measured for moisture content were taken from an area inside a large tire section to reduce any short-time moisture interchange through the exposed ends of the cords. The samples were in the form of 1/2-inch strips consisting of rubber on one side and exposed cord on the other. For the first ply (the ply next to the inner tube) these strips contained tire rubber that separated the cord from the inner tube, together with cords from the first ply, but did not include rubber found between the first and second plies. Each sample was pulled off and dropped into a tared weighing bottle with one quick motion in order to minimize the exposure of the bared cords to the room temperature. The bottle was immediately covered and weighed. Calculation showed that the amount of moisture exchanged between the cord and the air in the weighing bottle was negligible.

The second and third plies were next pulled off in the sample area, leaving the fourth ply covered with a thin layer of rubber. The ends of ply four were cut loose, seized with a pair of pliers, and the cords with adhering rubber pulled out in strips and placed into the weighing bottle as before. Samples from the seventh layer were obtained in a similar manner. With each ply the cords were kept covered with a layer of rubber until the instant the sample was stripped out and placed into the bottle.

The weight loss in drying the cord plus adhering rubber in an oven at 105° C. was determined in the conventional A.S.T.M. manner^{8/} with P₂O₅ as the desiccant. The sample was then exposed to room air overnight, and the rubber carefully picked off the cords. The dry weight of the cords alone was determined as before. Small strips of the ply rubber were also removed at the time of stripping from the tire and placed into weighing bottles. These were weighed and heated in the same manner as described for the original sample to obtain the weight lost by the rubber in the oven drying process. These weight losses were used as indicated below.

The moisture contents,^{9/} in per cent of dry weight of cord, were calculated for the original cords as shown in Table 1. Triplicate determinations were made on each ply tested. The agreement obtained between individual samples from each ply is indicated in the results shown in Table 2. In all other results the values shown are the average of three determinations.

8/ "A.S.T.M. Standards 1942, Part III," p. 1426. American Society for Testing Materials, Philadelphia, 1942.

9/ Moisture contents herein reported are all expressed in per cent. of dry weight of the cord. These values are the same as those frequently referred to in the textile industry as "moisture regains."

TEST RESULTS

Effect of Storage on Moisture in the Cords

Measurements were made on two cotton tires in a preliminary experiment to determine the effect of prolonged storage on the moisture contents of the cords. These tires had been made as experimental tires with a special cotton fabric under similar manufacturing conditions, of identical S-4 rubber compositions, and, in fact, by the same tire builder. They were of 7.50-20 size with non-directional military tread, eight body plies, and two cap plies. One tire (B) had been tested on the U. S. Army Ordnance Tire Test Fleet course at San Antonio, Tex.^{10/} The test was run during the summer months, when the maximum day temperature was between 85 and 105° F.; wet road conditions were encountered approximately one-fourth of the time. Under these conditions tire (B) ran 18,000 miles before failure. The other tire (A) was maintained in its new condition except for the fact that it had been plunger-tested. Both tires were stored under identical conditions, ranging from 80 to 100° F. and from 45 to 60% relative humidity, for a period of approximately nine months before the moisture determinations were made. The results are tabulated in Table 2.

These results are subject to some error due to a small indeterminate amount of rubber still remaining on the cord after separation. If, for example, 5% of the weight of the dry cord is rubber, then the moisture content as calculated would be larger by about 0.1%.

The moisture contents obtained by this method were checked for ply three of Tire B by a second, but possibly somewhat less accurate method of removing the cord alone from the tire and determining its moisture content directly. In this procedure the cord before being placed into the weighing bottle was first carefully separated from the rubber in the conditioned room. It was found that about 12 minutes were required to make this separation. From data obtained by following the weight loss of newly exposed cords it was found that owing to the choice of room conditions the cord lost an average of 0.6% of its dry weight during its 12-minute exposure. When this value was added to the average value of 3.63% found for the exposed cord, a total of 4.2% was obtained for the moisture content of the original cord. This agrees reasonably well with the results reported in Table 2.

Although the two tires here compared were produced by identical manufacturing processes and conditions, and therefore probably had similar moisture contents at the start, their contrastingly different service histories would lead to the expectation that their moisture contents would be considerably different. The data in Table 2, however, show them to have almost exactly the same moisture contents in the cords when the measurements were made. In view of the literature evidence relating to the transfer of water vapor through rubber, it seems reasonable to assume that the cotton cords in these tires had reached a moisture equilibrium characteristic of the nine-month storage conditions and that their individual histories had not appreciably affected their moisture sorption characteristics.

^{10/} For a description of this test course see B. J. Lemon and J. J. Robson, India Rubber World, 109, 463 and 582 (1944).

Effect of Exposure to Various Temperatures and Humidities

The experiment described below was set up to give some indication of the range of moisture contents possible to the cords in tires and of the rate of approach to equilibrium under various conditions. Four tires were used, two with cotton and two with rayon fabric, all from the same manufacturer. There follows a summary of the history of each tire.

TIRE C. Size, 7.00-20, S-4, highway tread, rayon fabric, 10 plies. This tire was run for a short time on the Government Tire Test Fleet highway course at San Antonio, Tex., but was removed because of a manufacturing defect. Its tread wear was almost negligible, and the tire was used in lieu of a new rayon tire for this test. Mileage—1,399 miles.

TIRE D. Same specifications as Tire C. These two tires were mates from the same test set. This tire had been run on the Government Tire Test Fleet course until the tread was worn through to the breakers. Mileage—43,246 miles.

TIRE E. Size, 7.50-20, S-4, mud and snow non-directional tread, cotton fabric, eight body plies, two cap plies. This tire had been used for plunger tests, but was otherwise new and undamaged. Sections used for moisture determinations were taken from areas between the plunger tests.

TIRE F. Same specifications as Tire E. These two tires were mates from the same set. This tire had been run on the U.S.A.O. Tire Test Fleet course which included 15% cross-country trails. Mileage—16,275 miles.

These tires were received at different times over a two-month period prior to the start of the moisture test. Figure 1 is a photograph of the four tires before they were cut into sections.

For this experiment each tire was cut into five sections. One of each of these was set aside for immediate moisture analysis. Two others were sealed at the ends by dipping into melted paraffin wax to prevent moisture transfer through the exposed ends of the cords. These sections were used in the low-temperature exposure conditions. The remaining two sections of the original five were sealed at the ends by dipping into molten Acrawax C at 140° C. This synthetic wax with a melting point at about 135° C. served to reduce moisture transpiration through the exposed cord ends at the higher temperatures. Observation at the end of the conditioning time showed the wax seals to be relatively free from cracking.

One section from each tire was exposed to each of the following conditions:

CONDITION 1. Temperature, 185-200° F.; relative humidity, 2%; exposure time, 54 days. The temperature is approximately the mean between summer temperature and the extreme high of tire temperatures. The humidity is that obtained when the laboratory air is heated to about 200° F. without loss of moisture. This condition was achieved by means of a large forced-draft oven.

CONDITION 2. Temperature, 70° F.; relative humidity, 60-65%; exposure time, 118 days. This condition was that prevailing in the textile testing laboratory in which the tire sections were exposed.

CONDITION 3. Temperature, 80-95° F.; relative humidity, 90-95%; exposure time, 106 days. This condition was attained in a special cabinet into which air at the proper temperature and humidity was injected at a continuous rate. This air was produced by passing a mixture of air and steam through a radiator condenser which was kept at the prescribed temperature.

CONDITION 4. Temperature, 200-210° F.; relative humidity, 80-100%; exposure time, 70 days. This condition was attained in a special heated cabinet into which a small amount of steam was injected at a continuous rate.

Tire sections were suspended or supported in the cabinets described above, so that only water vapor, and not liquid water, would come into contact with them.

Humidities at the higher temperatures were determined by measuring the weight of water vapor contained for a given volume of dry air, calculating the partial pressure of the water vapor, and then evaluating the quotient of this partial pressure divided by the vapor pressure of water at the same temperature.

Sections under Conditions 1, 2, and 3 were taken out periodically and weighed to the nearest five grams (the sections averaged about four kilograms in weight) on a precision high-capacity scale in order to follow their approach to moisture equilibrium. The percentage of weight change for these sections with time is shown graphically in Figure 2. All sections at the high temperatures of Condition 1 appear to have reached approximate equilibrium in less than 25 days. No appreciable change was noted for Condition 2. Under Condition 3 the sections from tires D and F, both of which had most of the tread rubber worn off, reached a constant weight in about 50 days, whereas sections from C and E tires were still gaining in weight when the final moisture analysis was made. These results are in agreement with the fact that moisture diffuses through rubber more rapidly at high temperatures than at low temperatures, and with the findings of Lyons,⁶ who showed that moisture diffuses out of a rubber slab more quickly than into it.

Moisture analyses of the sections exposed under each temperature and humidity condition were made as described above when it was thought the moisture contents were at reasonably stable levels. The results are tabulated in Table 3. The tabulation includes the average of the percentage of weight lost by the rubber in the oven drying process. Although this loss is probably largely one of moisture, there is some doubt concerning its completeness. Therefore the values reported for rubber cannot correctly be called moisture contents.

At the high temperatures and humidities of Condition 4, the synthetic rubber compound used in the tires suffered some deterioration, most noticeable on the outside layers of the rubber. This caused some difficulty in determining the moisture contents of the cords in ply one since it was not possible to make an accurate evaluation of the moisture lost by the outside rubber. For this reason the moisture contents for the tires under

Condition 4 are only reported to the nearest per cent and, at least for the first ply, are subject to an error in experimental determination of not more than 3% in moisture content.

From the data in Table 3, from the known behavior of moisture sorption and diffusion through rubber, and from the physical features of the tires used in the test, an approximation of the average moisture contents of the cords in the tires was made. These are shown in the charts in Figure 3. These data show that the new and used tires of each type have approximately equal moisture contents after being exposed to the same conditions for periods ranging from two to four months. For the same conditions of exposure, the cords in cotton tires have a lower moisture content than the cords in rayon tires. This concurs with the data of Wiegerink⁷ who found for rayon yarn a higher moisture content than that found for cotton yarn under identical conditions of temperature and humidity.

It is interesting to note from the results in Table 3 that the moisture weight loss for the rubber appears to be a function of the moisture contents of the cords in the same ply. When a dry tire is exposed to humid conditions, the rubber and cord would be expected to compete for the available moisture, since both materials take up water to a greater or less extent. Some idea of the relation between the water vapor uptake of the two substances may be obtained by plotting the moisture weight loss for the rubber against the moisture content of the cord for all tires. This has been done in Figure 4. There were found two distinct curves for this relation, one for the cotton tires and another for the rayon. The results indicate that both rayon and cotton are more hygroscopic than the rubber. When moisture diffuses into the tire, the moisture content of the fabric appears to increase much more rapidly than that of the rubber until the fabric approaches a fairly high value. After that the moisture in the rubber increases. Since cotton is less hygroscopic than rayon (see, for example, Wiegerink⁷), it does not seem surprising to find from Table 3 and Figure 4 that when cotton cord and rayon tire cord in tires have equal moisture contents, the rubber around the cotton cords holds more moisture than the rubber around the rayon.

Effect of Wheel Test Operation on Cord Moisture Contents

The experimental data described above do not completely satisfy the question of moisture contents of cords in tires because the effect of actual tire service might be considerably different from that of inactive storage. Truck tires operating on hot desert roads are known to develop rather high temperatures — conditions under which they might be expected to dry out sufficiently so that the tire fabric would lose most of its moisture. What would be the moisture content of cord in a tire after several days of such operation?

As a partial answer to this question the data in Table 4 are submitted. These results are from wheel tests made by the Armstrong Tire & Rubber Co., Natchez, Miss., and are for two pairs of rayon tires; the members in each pair differ only in the moisture contents of the cords built into the tires. It was not possible to evaluate the cord moisture in the tire immediately following vulcanization since this action would require damaging the tire. Actually, the

moisture content of the cords probably increased somewhat during building and cure since the raw rubber compound contained varying amounts of water, some of which may have been given up to the cord. The significant fact found in Table 4, however, is that after approximately 15 continuous days on a wheel test during which the inside of the tire was, by actual measurement, at a temperature of approximately 200° F. the moisture contents of the rayon cords were still as high as 5.73%.

CONCLUSIONS

The results of this investigation indicate that the environmental condition is the most important determinant of the moisture content of the cord in the tire. When the surrounding atmosphere is more or less constant, as in storage, the tire cord probably assumes moisture values which are in equilibrium with the average of these conditions. In a humid climate the moisture content of the cords would be expected to be rather high. Even when the tire is operated under conditions conducive to high tire temperatures, considerable time is required for the cord to undergo appreciable moisture loss through the rubber.

These conclusions lead to a number of significant consequences. If the tire is built under conditions where the fabric is dry, say with 2-3% moisture content, there is no assurance that the moisture values will be maintained at these low levels. Conditions of climate and operation which will keep the cords fairly dry probably exist, but indications are that they are not common.

The moisture and temperature levels at which cords are tested in order to predict tire fabric performance should take into consideration the moisture contents of the cords in the tire. Dillon and Prettyman^{11/} have shown that temperature and humidity exert profound influences upon the physical properties of tire cords. These results and the experiments on moisture in tires described in the present paper emphasize the importance of measuring the physical properties of tire cords over a wide range of moisture contents.

The authors are indebted to A. J. Slatter, W. M. Moser, and M. DeMarco of the Armstrong Tire & Rubber Co., Natchez, Miss., for the data on moisture contents of cords in wheel-tested tires, and to E. L. Skau of the Southern Regional Research Laboratory for his interest and encouragement in this work.

11/ J. Applied Phys., 16, 159 (1945).

Table 1. Sample Calculation of Moisture Content in Per Cent. of Dry Weight of Cord Taken from Tire Section

	Grams
(1) Weight of cord plus rubber as removed from tire.....	1.2942
(2) Oven-dried weight of cord plus rubber.....	1.2740
(3) Weight loss of cord and rubber in drying.....	0.0202
(4) Weight of rubber sample as removed from tire.....	0.8615
(5) Oven-dried weight of rubber.....	0.8604
(6) Weight loss of rubber in oven drying:.....	0.0011
(7) Per cent. loss of rubber (based on original weight).....	0.13%
Average of three determinations.....	0.14%
(8) Oven-dried weight of cord alone.....	0.4333
(9) Oven-dried weight of rubber portion of sample (2)-(8).....	0.8407
(10) Loss in weight contributed by rubber in oven-drying of cord plus rubber $\frac{(9)}{100\% - (7)} - (9)$	0.0012
(11) Loss in weight in cord alone (3)-(10).....	0.0190
(12) Moisture in cord $\frac{(11)}{(8)} \times 100$ (per cent. of dry weight).....	4.39%

Table 2. Moisture Contents of Cotton Cords in Tires Stored
for Nine Months
(Temperatures, 80 to 100° F.; Relative Humidities, 45 to 60%)

Tire	Ply	%			Average
		Sample 1	Sample 2	Sample 3	
A (new):.....	Third.....	4.39	4.46	4.50	4.45
B (run for ... 18,000 miles)	Third.....	4.45	4.49	4.50	4.48
	Fifth.....	4.56	4.56	4.61	4.58

Table 3. Moisture Contents of Cord and Adjacent Rubber in Tires C, D, E, and F as Per Cent. of Oven-Dry Weight

Tire	Ply	Sample	Original %	Conditions of Exposure							
				(1)	(2)	(3)	(4)	%	%	%	%
				185-200° F. 2% R.H.	70° F. 60-65% R.H.	80-95° F. 90-95% R.H.	200-210° F. 80-100% R.H.				
C-New Rayon	First	Cord	7.8	0.28	9.4	20.7		36			
		Rubber	0.58	0.09	0.46	2.19		66			
	Seventh	Cord	5.6	0.59	6.9	9.6		32			
		Rubber	0.57	0.08	0.42	0.53		2.5			
D-Used Rayon	First	Cord	6.7	0.37	9.3	17.1		45			
		Rubber	0.68	0.13	0.70	1.66		24			
	Seventh	Cord	4.1	0.71	6.9	11.0		39			
		Rubber	0.42	0.06	0.41	0.48		4.7			
E-New Cotton	First	Cord	3.8	0.17	4.8	10.4		17			
		Rubber	0.46	0.11	0.90	1.57		31			
	Fourth	Cord		0.23	4.2	6.4		17			
		Rubber		0.08	0.68	0.77		4.2			
	Seventh	Cord	3.0	0.28	3.8	5.0		18			
		Rubber	0.64	0.08	0.61	0.68		2.1			
F-Used Cotton	First	Cord	4.7	0.17	5.3	10.6		14			
		Rubber	0.41	0.05	0.56	1.58		16			
	Fourth	Cord		0.26	4.6	6.2		23			
		Rubber		0.03	0.57	1.00		10.7			
	Seventh	Cord	4.5	0.25	4.6	6.6		14			
		Rubber	0.65	0.07	0.55	0.83		12.1			

Table 4. Moisture Contents of Wheel-Tested
9.00-20, 10-Ply Rayon Tires

	Moisture Content of Rayon Cord - %			
	Tire G	Tire H	Tire I	Tire J
Before entering drying cans.....	4.14	4.14	3.03	3.03
Immediately after leaving drying cans.....	1.25	1.25	1.66	1.66
Immediately before entering calender.....	1.37	1.37	2.21	2.21
At bias cutter.....	1.44	1.44	3.06	3.06
At building machine.....	1.44	3.69*	3.06	7.25*
From wheel-tested tire (fifth plies).....	3.21	4.67	5.62	5.73
Wheel Test Data				
Room temperature — °F.....	100	100	100	100
Maximum temperature in shoulder of tire — °F.....	210	216	236	232
Miles run on test wheel**.....	4,102	4,106	6,119	10,965
Time of continuous running (at 30 miles per hour) — days.....	5.7	5.7	8.5	15.2

*The fabric for Tires H and J was allowed to regain moisture before being built into the tires.

**These mileages do not reflect tire performance since the tires were removed from the test wheel before failure.

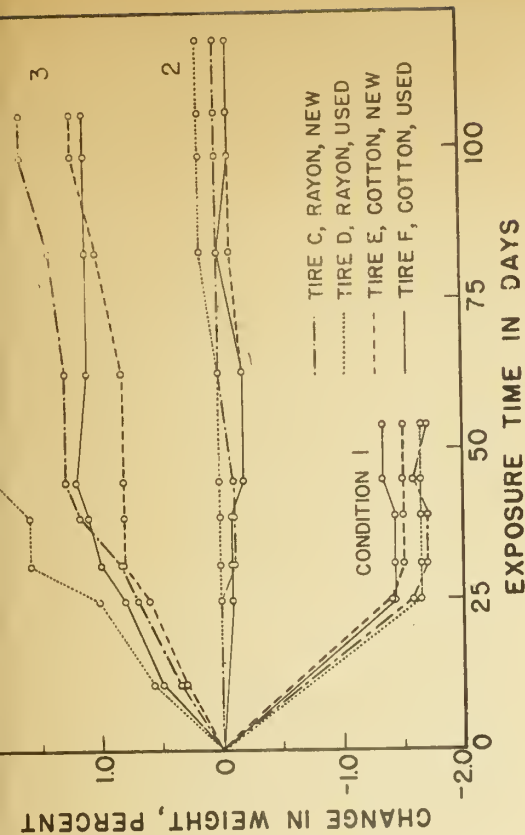


Figure 2. Weight change of tire sections during exposure to Conditions 1, 2, and 3.

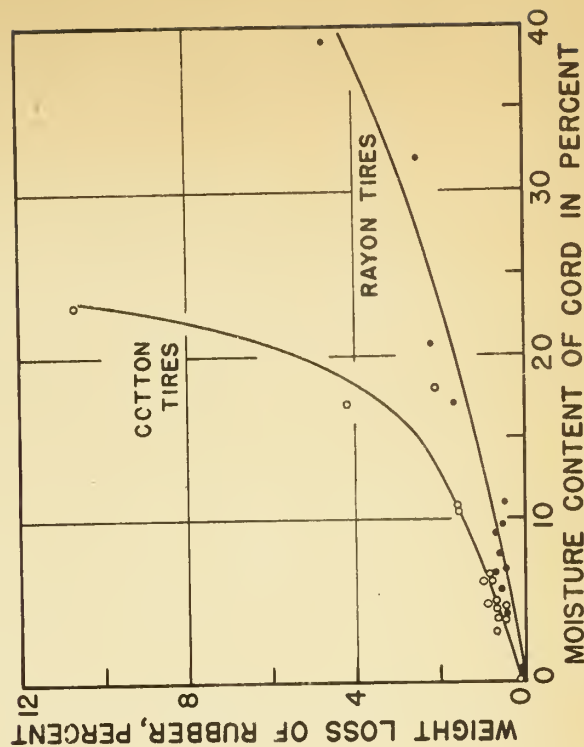


Figure 4. Relation of the percent moisture in the cord to the percent weight loss sustained by the rubber in the oven-drying process.

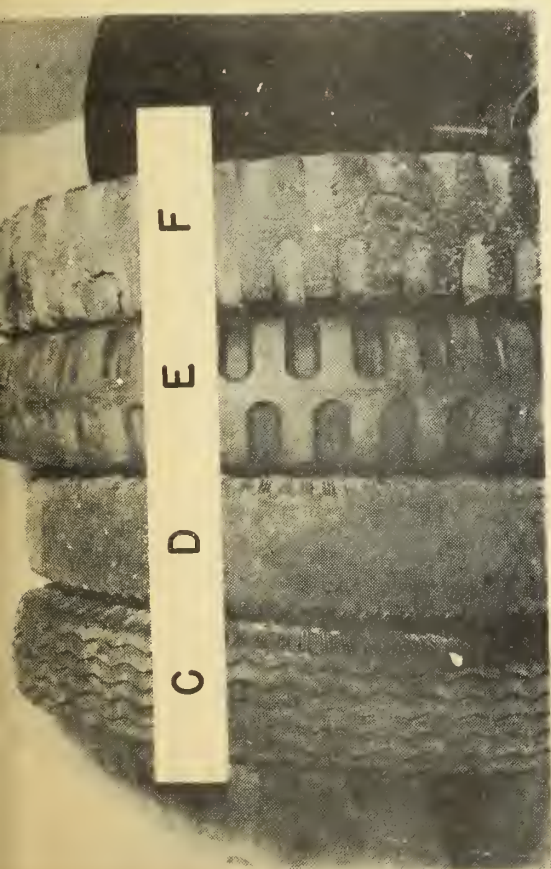


Figure 1. Tires used in tests for exposure to various temperatures and humidities. (For complete specifications and histories of these tires see text.)

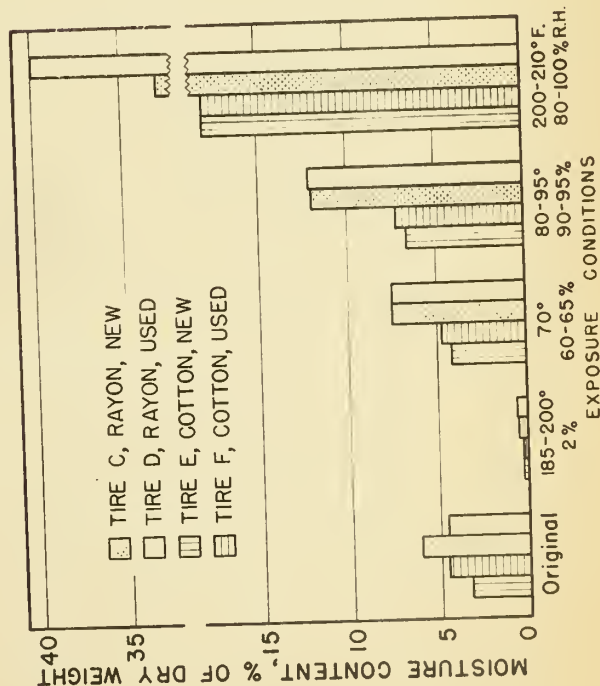


Figure 3. Estimated average moisture contents of tire cords after exposure.

